Advancements in Logistics Reduction Technologies for Exploration Missions

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Management of logistics on exploration missions includes both looking for ways to minimize the quantities, mass and volume of various consumables, supplies, spares, and equipment as well as ways to minimize the crew time needed for locating and handling those items. Also included are ways to minimize the waste, handling and resultant products from the processes of maintaining a crew on these missions. The Logistics Reduction project within Exploration Capabilities (ExCap) encompasses technologies for management of waste, trash, autonomous logistics, and clothing. This paper provides a status of work in these areas including recent accomplishments and challenges encountered. Future objectives will also be covered along with the work currently in progress. Specifically, the paper will cover technologies in waste management, namely, the Universal Waste Management System (UWMS) which is the exploration toilet and work on an alternative waste collection container, the Alternate Fecal Canister (AFC). Trash management technologies work on the Trash Compaction and Processing System (TCPS) and Trash to Gas (TtG) is summarized with progress to date as well as information on how jettison as an option is related. Progress and summary of recent accomplishment on the RFID (Radio Frequency ID) Enabled Autonomous Logistics Management (REALM) and the Autonomous Logistics (AL) technologies is detailed. Advanced Clothing System (ACS) and work in Systems Engineering and Integration

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(SE&I) is also included. Status of the technologies, accomplishments and how the focus areas inform program decisions will be addressed.

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Nomenclature

ACS = Advanced Clothing System
AI = Artificial Intelligence
ALM = Autonomous Logistics Management
AOWG = Advanced Organic Waste Gasification
BAA = Broad Agency Agreement
CEP = Complex Event Processing
CTB = Cargo Transfer Bag
CO_2 = Carbon Dioxide
DLP = Digital Light Projector
ExCap = Exploration Capabilities
FTIR = Fourier-transform Infrared Spectroscopy
GCMS = Gas chromatography-mass spectrometry
HEPA = High Efficiency Particulate Air
HLS = Human Landing System
HMC = Heat Melt Compactor
IR = InfraRed
ISS = International Space Station
IMS = Inventory Management System
LEO = Low Earth Orbit
LOO = Lavatory On-Orbit
LR = Logistics Reduction
M2M = Moon to Mars
MCTB = Multi-purpose Cargo Transfer Bag
MPCV = Multi-Purpose Crew Vehicle
NextSTEP = Next Space Technologies for Exploration Partnership
m^3 = cubic meter
NASA = National Aeronautics and Space Administration
OSCAR = Orbital Syngas/Commodity Augmentation Reactor
P&G = Procter and Gamble
PMM = Permanent Multipurpose Module
QR = Quick Response Code
REALM = Radio Frequency Identification Enabled Autonomous Logistics Management
RFID = Radio Frequency Identification
SBIR = Small Business Innovation Research
SCCS = Source Contaminate Control System
STMD = Space Technology Mission Directorate
TCPS = Trash Compaction Processing System
TGA = Thermogravimetric Analysis
TtG = Trash to Gas
TRL = Technology Readiness Level
UPA = Urine Processor Assembly
UWMS = Universal Waste Management System
VOC = Volatile Organic Compounds

I. Introduction

TECHNOLGIES for reducing crew consumable mass, reducing crew time for logistics management, and managing trash are being developed by the Advanced Exploration Systems (AES) Logistics Reduction (LR) Project. In addition to reducing mass, volume, and crew time, it is important that development directly address

exploration technology gaps[1] using a range of government and industry collaborations to enable the space economy. It is equally important that technologies have path that leads to validation as an International Space Station (ISS) technology demonstration (or suitable ground analog) prior to implementation into exploration architectures. Figure 1 shows alignment between the AES LR technologies and exploration gaps, mass reduction, and project goals.

The AES LR project scope includes 16 technology areas that primarily target crew consumables, logistics management, and waste management. This paper provides an overview of the technology development progress over the past two years and provides references to papers that provide additional details. Direct mass reduction of logistics is being investigated with longer wear crew clothing, compact toilets, optimization of fecal waste containers mass and volume, and on-demand manufacturing in lieu of dedicated logistical spares. Repurposing of items also reduces departure mass and can be achieved with laundering of crew clothing and reconfiguring cargo transfer bags from launch vehicles to habitat outfitting. Some logistics and waste products can be processed, and the products used for a secondary purpose, which prevents the need of launching the secondary item. This includes processing of fecal material and trash to recover water, processed trash can also supplement vehicle radiation shielding, and in-space manufacturing has the capability to convert broken items into manufacturing feedstock Trash can also be thermally deconstructed to gas and vented or cleaned up and used. Crew time is also very valuable for both short term and longer missions. Autonomous tracking of cargo saves crew inventory time, helps find lost items, and facilitates denser packaging. Autonomous manipulation of cargo can occur prior to crew arrival, during crewed periods, and manage trash after the crew departs, thereby allowing the crew to focus on science and critical vehicle maintenance.

	Mass Reduction Approach							LR Goals FY22+						
LR Technologies	Direct Mass Reduction	Reduces ESM	Improved Logistics Tracking	Direct Reuse	Processing for Second Function	Deconstruction to Gas	Autonomy and Automation	ISS TD in FY22	ISS TD in FY23	ISS TD in FY24	MPCV Infusion	Gateway Infusion	Mars/Lunar Infusion	SBIR infusion
Universal Waste Management System (UWMS)	Y	Y						Y		Y	Y	Y	Y	
UWMS Alt Fecal Container	Y	Y			Y			Y				Y	Y	
UWMS Pretreat Tank	M	M								Y		Y	Y	
RFID Enabled Autonomous Logistics - Fixed Readers (REALM-1)		Y	Y				Y	Transition to ISS sustaining				Y	Y	
REALM - Mobile Reader (REALM-2)		Y	Y				Y	Y	Y			Y	Y	
REALM - Dense Zone Reader (REALM-3)		Y	Y				Y	Y				Y	Y	
REALM - 6 Degree of Freedom (REALM-6DOF)		Y	Y				Y		Y			Y	Y	III
RFID Sensors		Y	Y				Y		Y			Y	Y	III
Trash Compactor Processing System (TCPS)		Y			Y					Y		M	Y	IIE
Autonomous Logistics (AL)			Y				Y					Y	Y	
Advanced Clothing Systems (ACS) - Long Wear Clothing	Y	Y					M		M	M	M	Y	Y	
ACS - Laundry		M		Y				Y	Y				M	IIE
Multipurpose Cargo Transfer Bags (MCTBs)		Y		Y						M		M	M	
Fecal Processing	Y	Y			Y							M	M	I & IIE
Trash to Gas (TtG) - venting/jettison		M				Y				Y		M	M	II
SE&I-Long Term Waste & Food Storage	M	M			M	M				M		M	M	IIE
In-Space Manufacturing	Y	Y			Y			Y	Y	Y		Y		

Legend: Y = Yes or Applicable
M = Maybe or Depends on Mission Assumptions
I, II, IIE or III = SBIR phase

Figure 1. Technologies mapped to exploration gaps, mass reduction type, validation, and mission infusion.

II. Metabolic Waste Collection Technologies

A new toilet was developed for use on long range exploration missions with the focus of reducing mass and volume and improving hygienic use for male and female crew members. The project provides two units; one which will be demonstrated and evaluated on ISS and one to fly on the Orion Artemis-2 mission. This toilet, the Universal Waste Management System (UWMS), builds on technologies used on Shuttle flights as well as that currently in use on ISS.[2]

The UWMS collects waste urine and feces and allows for removal of these wastes for further recycling of urine (ISS unit) or venting (Orion unit) and remote storage of the collected fecal materials. Both UWMS units rely on a common dual fan separator to remove air from the urine stream and to provide air suction to aid in collection of both

urine and fecal material. The dual fan separator utilizes a common motor for two fans and the liquid separator to reduce volume and mass. Hard-sided canisters with separate lids collect and were designed to store approximately 20 fecal deposits. Updated numbers from a returned canister show that number is significantly less at only 13. Details are provided in ICES-2023-038.[5] Both the urine funnel and commode seat are NASA designed components targeting improving usage by female crewmembers during simultaneous urination and defecation. Based on feedback from an on-orbit evaluation of the initial funnels with the ISS toilet, the design was updated to slightly shorten the height of the funnels to improve cleanability. Three funnel design options were flown for final evaluation with the ISS UWMS. Of primary interest is the use by the female crew members with the configuration including the UWMS.

The Orion UWMS was delivered to KSC 12/23/2019 and was installed into the Artemis-2 vehicle in March of 2020. The ISS unit was delivered in June 2020 and launched to ISS in October of that year along with Toilet Integration Hardware to allow installation and operation on ISS (Figure 2). The ISS UWMS unit is more complex than the Orion unit because of the addition of an active dosing assembly for delivery of accurate quantities of urine pretreat into the urine stream before it travels downstream to the Urine Processor Assembly (UPA) on ISS. The UWMS uses a dose pump to deliver defined volumes of water and pretreat concentrate, mix them, and then measure the conductivity before it is injected into the urine as it comes into the UWMS from the urine funnel and urine hose.

The Integration Hardware includes the Stall, Pretreat Tank Enclosure, Mounting Adapter, Data Recorder, Power Box and fluid hoses, and electrical and data cables.

The ISS unit started installation in December 2020 and a limited checkout was completed in November 2021. Completion of a technology demonstration on ISS is currently pending resolution of technical issues with the hardware and is planned for late 2023. A shorter Artemis-2 demonstration on ISS is planned for early calendar 2023. More information on the technical issues can be found in referenced papers. [3,4,5]

Figure 2. UWMS, ISS unit in Node 3 of ISS (left) and Orion unit installed in Artemis-2 (right)

A separate project developed an alternative to the hard-sided fecal canister that is part of the UWMS system. The design includes a flexible bag that is lighter than the machined aluminum canister and has a significantly smaller pre-use packing volume (Figure 3). The bag was designed to interface with the UWMS and associated accessories such as the fecal canister lids and the fecal compactor. The project delivered flight units to ISS and evaluation thru a technology demonstration is planned for late 2023.[5]

Figure 3. AFC in full configuration (left), stowed configuration (middle) and hard-sided Fecal Canister (right).

Future improvements for exploration toilet include the development of a urine pretreat concentrate tank for round trip Mars transit missions to improve containment, reduce the leakage potential and prevent pretreat degradation. Feasibility assessment work was begun in 2020 and will continue into 2023.

In addition, work has started on replacing the current seat and fecal bag on the ISS UWMS unit with a redesigned option that was developed as part of the Human Landing System (HLS) Lavatory On-Orbit (LOO) project[6]. Once delivered and installed, the crew on-orbit will evaluate the hardware for overall functionality and performance with the existing UWMS hardware. If proven successful, the plan will be to also replace the hardware on the Artemis-2 UWMS.

Beyond metabolic waste collection and storage, technologies for fecal processing to recover water and stabilize the waste are being investigated through Small Business Innovation Research (SBIR) contracts[7,8,9,10]. One of these efforts with Advanced Fuel Research investigated torrefaction of the feces at temperatures up to 250°C in a phase II-E contract. Another effort with Ultrasonic Technology Solutions has just begun a phase II-E contract focusing on using piezoelectric transducers to mechanically shake the water out of the feces with ultrasonic waves. The hope is that one or more of these technologies will be ready to support long duration missions where additional water recovery and/or stabilization of feces is needed.

III. Autonomous Logistics Management Tracking Technologies

Experiences with logistics management on the International Space Station have identified a critical need for automation in logistics management tracking technologies. While more remote habitats may not initially experience the volume of cargo that is now typical on the ISS, the cost and impacts of replenishing lost items or not having items when required is likely to be much greater. Items tracked in the database are considered “reportable items”, which are items for which the value of tracking exceeds the cost. Technologies deployed to track the reportable items can also vary depending on the criticality of the item. As tracking technologies mature, enabling tracking or more types of items within an acceptable cost range, the number of reportable items is expected to increase. NASA embarked on the RFID-Enabled Autonomous Logistics Management (REALM) experiments to study these technologies, to understand how to implement them on a remote outpost, and how to tailor the solution to meet different mission constraints. Following sub-sections detail the experiences with these technologies as well as forward work.

A. Overview

The REALM experiments were divided into three foundational phases, REALM-1, -2, and -3. REALM-1 comprises a constellation of fixed readers and antennas in the open region of instrumented ISS modules. REALM-2 is based on a robotic free-flyer equipped with an RFID reader and antennas, and REALM-3 is based on a fixed reader similar to REALM-1, but with the signals routed directly into dense stowage regions. All data is downlinked to a Complex Event Processing (CEP) center where the data is reduced to key inferences, chief of which is item location.

B. REALM-1

The REALM-1 constellation on ISS consists of 2 readers and 8 antennas in each of NODE 1, US LAB, and NODE 2. The intent of the REALM-1 system is to be monitoring these modules on a “24/7” basis to, at a minimum, provide awareness as to “last seen” awareness at least at the ½-module resolution. Raw data, including signal strength and phase, number of reads, frequency channel, and antenna associated with the read, are downlinked to the ground-based CEP for data reduction. Five different algorithms have been used with REALM-1 data to derive location estimates. Earlier attempts were based on regression algorithms that result in coordinate-based locations. More recently, machine learning classifiers (Random Forest and a Deep Neural Net) resulted in improved location accuracy. Figure 4 below shows the root mean square error in cm as a function of the total tag population in instrumented areas. Figure 5 is a similar representation for tags in non-instrumented areas. Although these areas are not instrumented, the RF signal from adjacent instrumented modules allows for some degree in localization. Although the performance in non-instrumented modules is not as good, it has proven to be useful. In general, an accuracy within the confines of a 1-meter is desirable. This suggests that additional tracking technologies are required to close the gap.

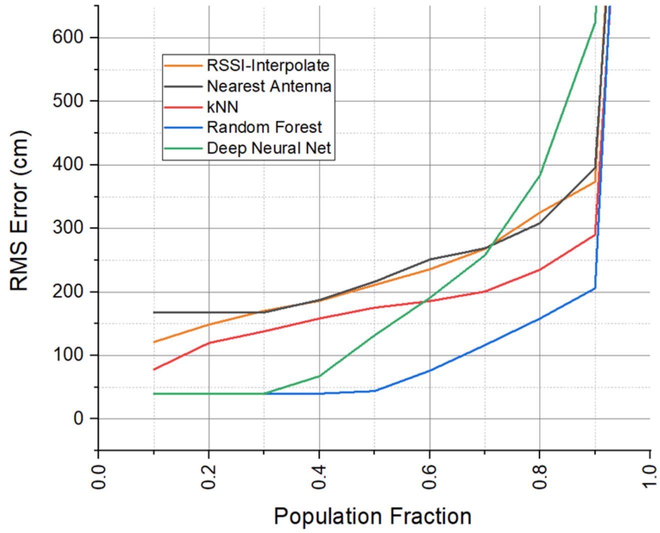

Figure 4. RMS error as a function of tag population fraction in instrumented modules.

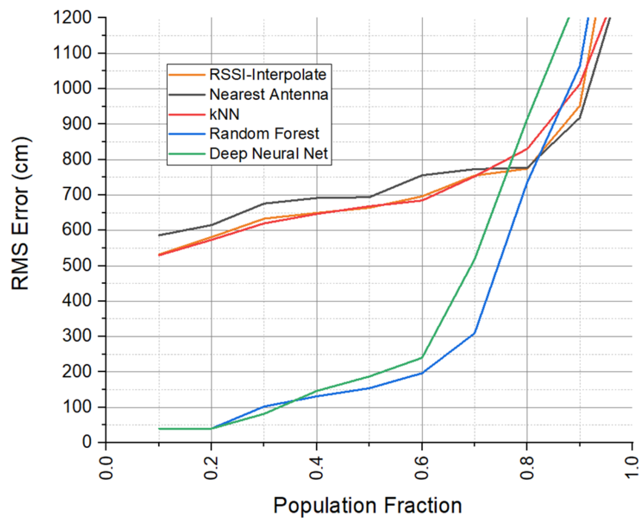

Figure 5. RMS error as a function of tag population fraction in non-instrumented modules.

C. REALM-3

REALM-3 is based on RFID reader antennas integrated within or behind the stowage racks to decrease tags that are obscured from the REALM-1 system, and to improve the localization accuracy. The specific ISS implementation with embedded antennas is referred to as Smart Stow. It comprises 4 textile quadrants that fit into

existing compartments of a textile ISS ZSR (zero-gravity stowage rack). The flight-like prototype Smart Stow in a mockup can be seen in Fig. 6, left side. While early ground testing indicates that RFID signals introduced into metallic stowage containers provide better read accuracy than non-metallic containers, Smart Stow was designed without metalized boundaries to simplify integration.

Each quadrant of Smart Stow has an embedded antenna system called HYDRA (HYper-Distributed RFID Antenna), a glimpse of which is shown in Fig. 6, right side. HYDRA is a switched multiplexer antenna system that connects to an RF port of a reader and powers itself by harvesting a small fraction of the incident RFID signal to run an internal microcontroller and switch. Each HYDRA node can connect to other HYDRA nodes or to antennas, all of which are switched so that only one antenna is active at any time. In the combined four quadrants of Smart Stow, HYDRA contains 24 antennas, the same as the entire REALM-1 constellation in 3 ISS modules. In contrast to the REALM-1 system, which utilizes 24 RF ports on 6 readers, Smart Stow only uses 2 ports on a single reader. Although this is more instrumentation than required in a single rack, the architecture permits flight testing of a HYDRA network with many branches and 3 levels of HYDRA nodes. Such an extended HYDRA network, when distributed throughout a habitat module, is anticipated to be a major factor in closing the performance gap discussed under the REALM-1 section.

The REALM-3 Smart Stow was commissioned in Q1 of FY23. Although it has already demonstrated a greatly improved capability to read items missed by the REALM-1 system and to locate items more accurately, data analysis is in work to determine the quantitative impacts. Moreover, in addition to the greater accuracy achieved for items located inside Smart Stow, it is anticipated that the machine learning algorithms will exhibit higher accuracy for items outside of Smart Stow as a further consequence. To realize the HYDRA technology on the larger scale of a vehicle, the components must be of a sufficiently low mass, especially the antennas, which appear in greater number than any component in the HYDRA architecture. The antennas in Smart Stow, which appear on the side walls in the right side of Fig. 6, are a new antenna created from a combination of fabric and printed circuit materials, weighing 31g each. For future implementations of HYDRA, a version using only rigid materials is under development to allow for rigid attachment and fasteners and improved manufacturability. The expected mass of this version is about 50g each, made possible by a printed Titanium base that is described in Section IV, "Additive Manufacturing and Logistics Reduction". Figure 7 shows the relative sizes of the REALM-1 and HYDRA antennas. The REALM-1 antennas, a patented technology, represent a significant size reduction compared to most RFID antennas. It would likely remain in use for coverage in the dimensions of a long axis of a cylindrical habitat, owing to the greater surface area and resulting gain. For stowage areas and radial coverage, the smaller, lower-mass HYDRA antenna is advantageous.

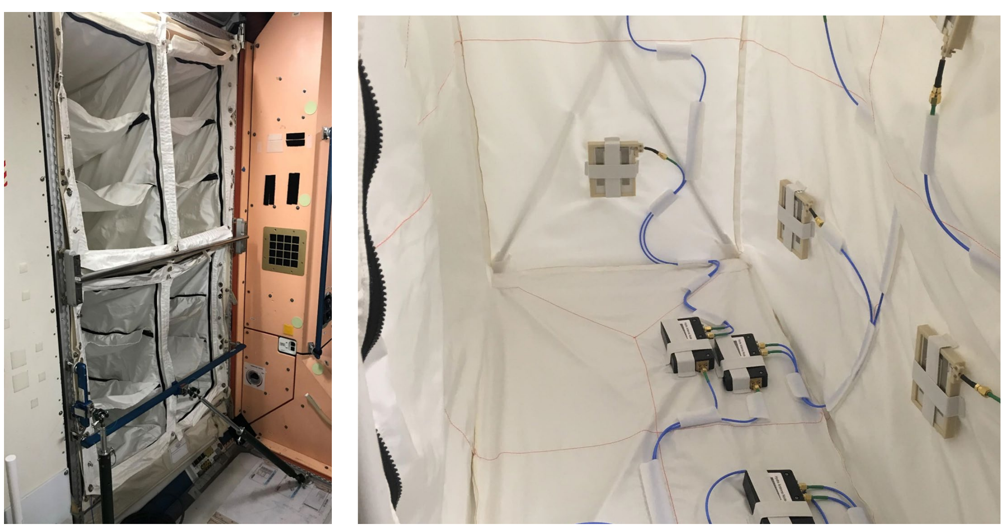

Figure 6. Smart Stow shelves (left) and HYDRA instrumentation behind liner (right).

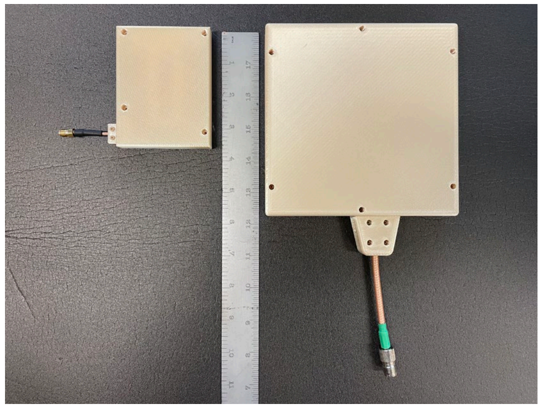

Figure 7. REALM-1 (right) and HYDRA (left) antennas.

D. REALM-2

REALM-2 is an RFID payload, including a reader and antennas, on a robotic free-flyer called Astrobee. It has been operating on ISS since 2020. Its primary attributes include the abilities to conduct inventory audits and to home on single targeted tags within about 8 inches. Figure 8 shows the REALM-2 system on Astrobee while perched in the ISS Permanent Multipurpose Module (PMM) . Since the PMM is not instrumented, and is not adjacent to an instrumented module, the REALM-1 system is unable to detect the majority of tagged items in the PMM. During this REALM-2 mission, the combined tags seen by REALM-1 and REALM-2 reached 2,021 of a reported 2,819 total RFID tags on ISS at the time. In contrast, REALM-1, alone, only read 1,404 of these tags.

Figure 8. REALM-2 on Astrobee free-flyer, perched in ISS PMM.

E. Forward Work

Currently, data reduction is on the ground. Ground controllers have access to the REALM database through a web tool, which provides information on asset locations and permits manual updates to the ISS Inventory Management System (IMS). A direct connect between the two databases is in work, as are updates to the crew graphical user interface which will give the crew access to RFID location estimates in addition to the legacy human-informed locations. Work on computationally lighter, machine learning algorithms are also in work with the objective of eventual remote operation of the CEP function. Other forward work includes vehicle-wide integration of a HYDRA system and adjustments to the CEP to leverage the increased data context.

IV. Additive Manufacturing and Logistics Reduction

The LR project has been working on incorporating new additive manufacturing technologies as additional opportunities to reduce launch mass and/or improve performance of the REALM system.

In-Space Manufacturing (ISM) activities have been evolving over the past several years[37] but are a recent addition to the AES LR project. There are synergies with manufacturing of REALM antennas and housing (the REALM-2 flight housing is additive manufacturing (see Figure 9)). There are SBIR technology developments by Cornerstone[38] for replacing packaging foam with printed lightweight structures that can be processed into manufacturing feedstock.

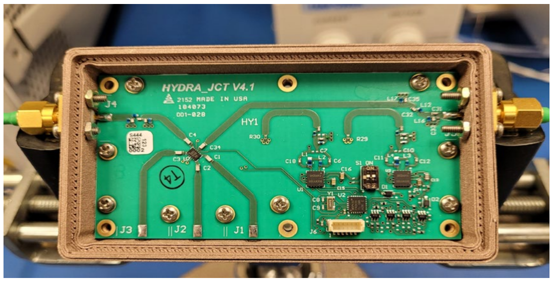

Figure 9. HYDRA PCB in ISM 3D-printed housing. Weight: 56% of AL housing, RF loss: 2.25 dB, 1.8 dB for AL

New ISM capabilities in additive electronics have been incorporated for printed wireless sensors on RFID tags and for the additive fabrication of conductive housings for performance and shielding. These new AM techniques allow for significant weigh savings without a sacrifice in system performance.

In addition, LR has worked with ISM to design and fabricate new titanium RFID antenna bases to replace bulky polymer/metal composite bases used in the past. These new titanium bases are much lighter and stiffer as antenna bases, leading to significant weight reductions and the potential expansion of the REALM system with additional nodes for performance enhancement.

These new AM parts were designed from the start with additive manufacturability considerations, so they take full advantage of this new processing capability for reduced weight and volume. Redesigns and updates will be much easier in the future with on-demand printing. NASA will have this capability on ISS in 2024, so these parts and new designs can be on-demand additively printed in space for immediate implementation and replacements.

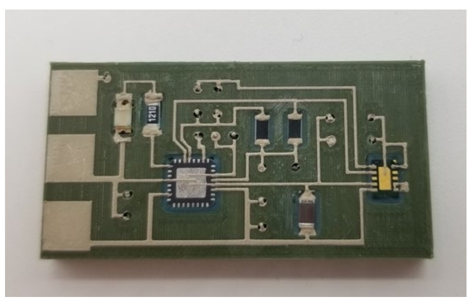

Figure 10. Additively manufactured Carbon Dioxide (CO_2) sensor

V. Trash Processing Technologies

Trash processing requires reducing the volume to gain back valuable storage and habitable space. Biological control and safening of the trash is needed for crew health and safety. Recovering water from the trash is highly desirable, and the residual dry trash has properties that can be utilized to convert to useful gases for fuel or commodity use, solids that will contain carbonaceous ash with crop nutrients and metals. The processed residual trash must be in a stable physical form and biologically inert for long-term storage.

A trash management strategy is needed for exploration missions and is useful for current strategies in dealing with trash on ISS. Logistics Reduction is working various technologies to deal with trash on various exploration vehicles, habitats, and missions. The selected technology (ies) will be optimized for each application and will include a combination of the options currently being developed. The strategies include use of a jettison mechanism, compaction of trash both with and without a heat element, and reduction of trash to a gas element. Studies are underway to evaluate how each of these can be used either alone or in combination. Trash compaction and trash to gas technologies will result in a demonstration on ISS along with ground testing of hardware.

A. The Trash Compaction Processing System (TCPS)

The TCPS is a waste management technology whose objectives are to reduce the volume of trash, safen processed trash to reduce risk of biological activity, stabilize processed trash for efficient storage, and to recover water and manage gaseous effluents. The TCPS has been in development at NASA for nearly two decades.

On Aug. 26, 2022, the NextSTEP Broad Agency Agreement (BAA) Phase B contract modification was awarded to Sierra Nevada Corporation of Madison, Wisconsin[11]. The period of performance is from Sept. 1, 2022, through Aug. 31, 2027, ending in an ISS flight demonstration with the possibility for continued use to support ISS operations.

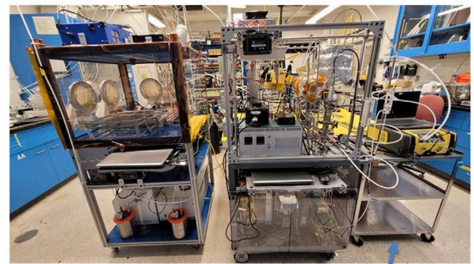

Figure 11. Source Contaminate Control System testing at ARC

Our risk reduction activities to support this project include using of a Source Contaminate Control System (SCCS) to remove toxic gaseous effluents from the TCPS. The SCCS consists of carbon adsorbent beds and a catalytic oxidizer (Figure 11). Quantitative measurements of volatile organic compounds (VOC) concentrations before and after processing characterize the system efficiency. Another activity is to characterize the particulate matter released during the TCPS operations. Size, density, and morphology of the particles were evaluated. Finally, a benign trash composition has been determined to limit the materials to be processed in the TCPS if the gaseous effluents were to be vented directly to the ISS cabin with no processing and still be safe for the crew to breath.

B. Planetary Protection Policy Applied to Waste Management

This task is to apply planetary protection policy to waste management. The objective of this task to develop the ability to contain all waste products to prevent microbial release for long durations and leave waste on planet surface while upholding planetary protection requirements. This includes the assessment of storage containers for harsh planetary environments, their expected lifetime, outgassing, position tracking, and identification of contents. Also need to determine if traditional High Efficiency Particulate Air (HEPA) filter-element bonding agents' are compatible with a very wide range of surface environments. In addition, need to develop passive unheated surface venting/filtering technologies for surface waste disposal that is compatible with wide range of surface temperatures (-170C to +130C) and high water vapor transfer until waste is dry to prevent microbial release for >50 years.

C. Jettison[12]

Many methods of waste processing are currently being developed by NASA, including developing new technologies to reuse and repurpose waste materials. However, even after processing and re-using as much as possible, the remaining waste must be discarded. The most cost-effective, reliable, and safest method to address these problems may be to simply jettison the materials from the spacecraft.The launching system is designed to have low mass, stowable, easily integrated to an airlock, simple to use, low power consumption, able to handle many different types and shapes of waste products, safely and reliably.

D. Waste to Base[13]

This project is to develop low Technology Readiness Level (TRL) concepts into workable solutions for issues in trash management, CO_2 processing, foam re-processing, and fecal processing. As needs change throughout a mission's lifecycle, trash and waste, broken components, and non-functional equipment can be reprocessed into new products such as replacement parts, structures, radiation shielding, and storable non-toxic solid propellant. Any salvaged material is a bonus for the mission rather than have it discarded. A recent (June 2022) crowdsource challenge under the Space Technology Mission Directorate (STMD's) NASA Tournament Lab was completed with 22 prizes awarded in the categories of CO_2 removal, trash processing, fecal processing, and foam packaging processing. Current activities are to down select these concepts for further development.

E. Manual Trash Compactor

This task is to design a manual, low mass, low volume, and easy to use manual trash compactor for use while in transit or on a planetary surface. Current activities include a review of previous work and a survey of potential

customers. If the compactor will use bags to contain the trash, they should already be found in the spaceship or surface habitat. Sufficient compaction pressure should be created to form a dense, storable trash tile. Low power, mass, and volume will be design drivers for this system and ease of use is also of primary importance. Estimates will be made for mass, power, and volume of a candidate conceptual design as part of this activity going forward.

F. Trash-to-Gas and Trash-to-Supply-Gas Processing Technologies

Trash processing requires reducing the volume to gain back valuable storage and habitable space. Biological control and safening of the trash are needed for crew health and safety. Recovering water from the trash is highly desirable, and the residual dry trash has properties that can be utilized to convert to useful gases for fuel or commodity use, solids that will contain carbonaceous ash with crop nutrients and metals. The processed residual trash must be in a stable physical form and biologically inert for long-term storage. Two development paths for solid trash deconstruction using thermal degradation techniques are Trash-to-Gas (TtG) and Trash-to-Supply-Gas (TtSG). TtG and TtSG systems can be tailored to mission needs; TtG primarily focuses on trash solid deconstruction to gas, which could then be vented overboard a spacecraft; TtSG primarily focuses on maximizing recovery of water and useful gases from the waste. TtSG also seeks to recover as many items as possible for mission reuse, including metals and carbonaceous ash, depending on the thermal degradation technique (i.e., combustion, pyrolysis). These systems enable trash volume reduction in the habitable spacecraft, and stabilizing the waste, which could minimize the possibility of unwanted microbial activity on a spacecraft. Several TtG and TtSG technologies have been explored, such as pyrolysis, torrefaction, incineration, and plasma, and traded to better understand which processes may be preferable for certain mission scenarios and applications[14,15].

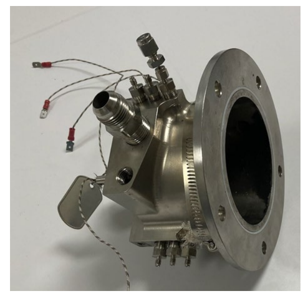

Figure 12. Subscale Trash to Gas OSCAR reactor

In 2019 and 2021 microgravity demonstrations of sub-scale TtG design concepts (Figure 12) were tested on the Orbital Syngas/Commodity Augmentation Reactor (OSCAR) system. The OSCAR test rig was originally configured for a hybrid steam and oxygen thermal degradation process with early testing in 2-second and 5-second microgravity tests[16]. Subsequent suborbital flights demonstrated up to 3 minutes of microgravity operation and data collection.[17-19] The microgravity testing of the OSCAR sub-scale system investigated design functions such as ignition, heat transfer, fluid flow and automation. OSCAR suborbital flights performed combustion reactions with a solid-to-gas conversion of ~28-55% for microgravity performance, while ground testing resulted in ~45-62%. CO_2 was the primary gas product for all OSCAR tests. Longer duration ground tests with more optimized parameters (> 3 minute suborbital runs) had >90% solid-to-gas conversion. An extensive gas analysis is underway to report which compounds may be of interest to mitigate or eliminate based on NASA exposure guidelines in a spacecraft[20]. The successful microgravity testing has provided confidence for ground design of a TtG unit, which is currently under development for a 4-crew system as a ground demonstration unit. The ground demonstration followed by potential Low Earth Orbit (LEO) destinations would pave the way for risk reduction to use for future Mars transit or surface destinations. The ground unit under development is aimed to decrease waste volume (i.e., increased habitable volume), enable mission resource recovery (i.e., Water (H_2O), Oxygen (O_2)), Methane (CH_4.), as well as minimize orbital debris and consider planetary protection waste material concerns.

Figure 13. OSCAR Reactor with ~22grams of shredded TCPS tiles

A commercial SBIR Phase 3 contract is underway with Pioneer Astronautics. They have developed the Advanced Organic Waste Gasification (AOWG)[21]. The AOWG system converts space simulated trash to water and dry gases suitable for venting or use as propellant. The technologist utilized in AOWG include steam reformation, and electrolysis to convert organic waste into water and a small amount of inorganic matter and other gaseous products. During Phase 3, AOWG continues to optimize the overall automatic processing of more advanced wastes such as fecal canisters, fecal plate processing, and wet and dry trash from the Heat Melt Compactor (HMC) tiles produced at NASA Ames Research Center. Pioneer is addressing some risk reduction developments by analyzing and mitigating harmful gas production, such as any remaining VOCs, and performing sizing analysis for a 4-crew system for future human exploration missions.

Additional commercial efforts include the Ignite SBIR Phase 1 contracts awarded in 2023 to Cecilia Energy who will investigate waste plastic to hydrogen using a catalytic conversion process, and re:3D, Inc. who will investigate additive manufacting with recycled space polymers.

Lower technology readiness level developments are underway at NASA for TtG and TtSG advancements, primarily in periphery components that would make up a total system. The funded developments include metal recovery from remaining solids for use in additive manufacturing applications (STMD 2023 work in progress), as well as investigating an optimal trash preparation and feed system[22] Modeling work is also underway to compare how different feedstocks may impact the overall TtG, TtSG, TCPS and venting systems during different mission scenarios (STMD 2023 work in progress). For example, the TCPS process of drying and compacting bulk waste items may complement TtG processing; TCPS tiles have been successfully processed in both OSCAR and AOWG in the forms of compacted and shredded tiles.

Public crowdsource efforts have also been performed to aid in TtG developments including "Recycling in Space: Waste Handling in a Microgravity Environment Challenge" [23]] and "The Trash-to-Gas Ash Management Challenge [24]]. These efforts have provided direct design feedback and considerations into current developments.

Advanced Clothing Technologies

Currently clothing represents about 25% of an astronaut's crew provisions (excluding food) and there are no current washer/dryers certified for space. Thus, LR's Advanced Clothing Systems (ACS) task is exploring longer-wear and lighter-weight clothing as well as low-resource-use methods of cleaning clothing for Moon to Mars (M2M) missions. Conventional water-based laundry system has not traded well for microgravity transit missions less than a year,[25]; however, through cooperation with the EC Life Support project's work on planetary water systems, new work toward low-water laundry in partial gravity is underway. Since it is critical for design of future water systems to know the composition of wastewater, having an optimum detergent or cleaning agent for clothes laundry was a priority. Through a Space Act Agreement with Procter and Gamble (P&G), researchers developed Tide Infinity detergent to meet the constraints of being fully degradable and compatible with closed loop air and water systems[26]. By developing a traditional laundry process for clothes cleaning on the moon and Mars it is expected that Earth based experience can be leveraged for both detergent chemistry and washer/dryer performance. Conversely it is hoped that advances to meet the strict resource constraints of planetary habitats can also feedback to improvements in laundry on Earth. Tide Infinity and a low-water, low-energy wash/dry cycle are being evaluated in commercial washer/dryer combination machines in several NASA tests including a bioreactor water processor at Texas Tech University[27] and the Crew Health And Performance Exploration Analog (CHAPEA) at JSC[28] (Figure 14).

Figure 14. Washer/Dryer unit in CHAPEA with Tide Infinity detergent

Another technology being developed by the ACS team in collaboration with the EC Life Support project's air team and small business partner Faraday Technologies is an in-situ hydrogen peroxide generator. This technology can reduce launch mass by allowing housekeeping disinfectant wipes to be wet on-orbit using hydrogen peroxide produced from recycled water.[29] Ground testing and hardware lifetime improvements are currently underway at JSC.

Another important technology gap the ACS team is working to close is compatibility of clothing with high oxygen atmospheres that will likely be found in exploration habitats where frequent spacewalks are planned. Clothing for ISS is certified to meet flammability requirements up to 30% O_2 at 10.2psia, but capability up to 36% O_2 at 8.3 psia is desired for planetary habitats. Several SBIR and STTR contracts are underway looking into fire retardant treatments as well as fundamentally lower flammability fibers.

VI. Systems Analysis and Integration

To ensure that LR developed technologies help close gaps and benefit M2M missions, technology roadmaps, key performance parameters, systems analysis and trade-off studies are continually updated. Since on-board waste management is a particular challenge for longer human missions and an opportunity for resource recovery and reuse, LR studies are exploring optimal waste processing, storage and/or disposal for each mission of interest to NASA. It is not one size fits all. For example, some high energy vehicles such as a Mars Transit Hab have a very strong driver to get rid of waste during the mission to reduce vehicle mass and thus propellant use. Although the TCPS technology described above can reduce the trash volume and recover water, trash and human waste may still need to be jettisoned on the way to Mars. Therefore, different trash jettison options have been analyzed using a systems

engineering approach[30]. An even broader integrated waste study is underway in which waste management strategies will be linked to mission level integration questions such as level of water closure, radiation shielding and mission risk. As mentioned above, different missions have different drivers which can strongly affect optimal waste management plans, so each reference mission in the M2M architecture will be studied individually.

VII. Conclusion

Logistics Reduction continues to work with numerous programs, providers and organizations preparing for Mars and Lunar missions. As these efforts become better defined, the work that LR is doing will inform decisions on hardware and operational strategies.

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